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Air-Cooled Engines For Vehicles

By

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Air-cooled engines are a commonplace powerplant for aircraft but the air-cooled principle has not found continued acceptance in motor vehicles except in those intended for military use. It is appropriate to examine the air-cooling principle as applied to vehicles in the light of recent developments in this field and reappraise the possibilities. In order to give the pertinent arguments, the details of a line of vehicle engines developed by Continental will be discussed.

Continental has been building air-cooled engines for tracked military vehicles since 1932, and these have been primarily aircraft engines of the radial type with modifications for vehicle use. During the latter part of the recent war, a special air-cooled engine having essential features for tank service was developed. Immediately following the war, a review of experiences indicated that great military benefits could be obtained by the use of a line of engines having maximum interchangeability of parts over the power range 100 to 1,000 H.P. In accordance with the parts interchangeability principle, an engine line was developed utilizing two basic cylinder sizes and ranging in cylinder numbers from four to twelve. Figure 1 gives one view of each of the small bore engines and Fig. 2 shows the large bore engine line. Execution of the fundamental design policy required the following:

1. Maximum interchangeability of parts.

2. Lightest weight consistent with the service required.

3. Minimum bulk.

4. Arrangement which permits the best utilization of space with serviceability in the vehicle an important consideration.

5. Must use Ordnance established gasoline (80 octane with maximum lead 3 cc/gal.) and oils.

6. Water-proofed so that water submersion would not interfere with operation.

7. Suitable for extremes of Arctic and Tropical climates.

Interchangeability of parts is construed to mean parts having a high wear rate and, obviously, this includes bearings, cylinder bores, valves, pistons and rings, in addition to spark plugs, oil seals, etc. It will probably be conceded by experienced engine operators that such parts as crankcase and other larger castings are not high mortality parts in a well-developed engine, and some of these parts cannot be made interchangeable between engines having varied numbers of cylinders. The main wearing parts are all associated with the individual cylinder and, by keeping the cylinders in single units, the interchangeability requirement is admirably served. In addition to this, the individual cylinder construction is especially suitable but not requisite to air-cooling arrangements.

The power range from 100 to 1,000 H.P. is covered by using various numbers of cylinders of two basic sizes. These sizes are 4-5/8-inch bore, 4-inch stroke, resulting in 67 cu.in./cylinder displacement and 5-3/4 bore, 5-3/4 stroke, resulting in 149 cu.in./cylinder displacement. Figure 3 is a photograph of interchangeable parts of the 149 cu.in. cylinder and Fig. 4 shows the 67 cu. in. cylinder interchangeable parts. Figures 5 and 6 show the similarity of the small cylinder line insofar as the non-interchangeable parts

are concerned. This integration permits many manufacturing economies as well as resulting in manufacturing flexibility.

Other information on the various models of engines is given in Table I. Although it would appear at first that there might be little interchangeability between the two cylinder lines, there is a considerable number of parts which are common to the two sizes of engines. Such components as fans, fan drive clutches, magnetos, oil filters, spark plugs, governors, etc., have been selected to be suitable for both engine sizes. In addition, a considerable number of standard parts are identical in both sizes of engines.

There was no hesitation in recommending the air-cooled cylinder principle since a great wealth of experience has been accumulated during the last fifteen years in tanks and in large and small aircraft, and this background was used effectively in developing the air-cooled vehicle line of engines.

Military advantage of the air-cooled engine is attested by the results during the last war, and the attitude of the U. S. Army Ordnance Department has been summarized in a paper by Col. J. M. Colby (Ref. 1). The air-cooled engine gives freedom from plumbing difficulties and insensitivity to extremes of climatic temperature, in addition to other advantages discussed later.

The performance of the 67 cu. in. cylinder and of the 149 cu. in cylinder is given in Figs. 7 and 8, respectively. These performance figures are the equal or superior to most liquid-cooled engines used in vehicles today, and such performance could not be obtained without cooling equal to the liquid-cooled engine.

The difficulty of cooling is a function of the heat input and is measured by the ratio, Indicated Horsepower/Thermal Efficiency, or since friction and thermal efficiency do not vary greatly at a given speed and compression ratio, it is permissible to use BHP/cu.in. as the heat load criterion. At rated power this figure is about .47 HP/cu.in. which is somewhat higher than in liquid-cooled vehicle engines, as shown in Fig. 9. In large highly supercharged, air-cooled aircraft engines, however, the cooling load is customarily more than twice as great.

The object of engine cooling is to hold metal temperatures at the combustion chamber and cylinder walls to safe limits from the stress and lubrication standpoints; therefore it is of interest to consider the cooling process. It can be assumed that the temperatures at the inner walls of the cylinder bore and combustion chamber wall are equal on both air-cooled and liquid-cooled unsupercharged engines since detonation and oil performance are substantially equal on the two types. From air-cooled cylinder temperature measurements, it is fairly definite that the cylinder bore surface temperature is 300° F and the combustion chamber surface is 550° F with heat load of about .47 HP/cu.in. and typical cooling conditions.

The data shown in Fig. 10 is an estimate based on cylinder temperature measurements and on the very extensive investigations of the N.A.C.A. and others (Ref. 2). This curve shows how the cylinder combustion chamber wall temperature varies with fin depth holding cooling air pressure drop at 5 inches H_2O and heat input at .47 HP/cu.in. With fin depth of 1 inch, the metal temperature at the combustion chamber wall is 500° F and the average fin temperature is 380° F. A point of interest in Fig. 10 is the high temperature of the fin metal out to the tip, which illustrates a basic point of superiority of the air-cooled engine over the liquid-cooled. Because of the higher temperature differential between the cooling air and the fin metal in the air-cooled engine, the cooling air required to maintain safe temperatures is about one-half that required for a comparable

liquid-cooled engine. If the point "A" in Fig. 10 (380° F) be taken as representing the average temperature of the fin metal and the ambient air on a hot day is 120° F, the temperature differential between the cooling air and metal is 260° F, while the differential between the liquid-cooling radiator (180° F) and cooling air is 60° F. The 260° F differential temperature is not maintained over the entire path of the air through the fins and, in addition, some air is passed through areas with lesser metal temperatures. The result of this is to reduce the average differential to about 150° F and this results in cooling air temperature rise on air-cooled vehicle engines of about 100° F at rated power with 120° F ambient temperature.

The liquid-cooled engine, however, has a slight advantage in that less care in design need be exercised to accomplish good cooling at the hotter areas, but at the outputs used in air-cooled vehicle engines, there is no problem in arranging the air paths to adequately cool all critical areas. At higher output, such as is used in large aircraft engine, greater depth fins (up to 3 inches) and greater cooling air pressure differentials (up to 20 inches H_2O) are used to give safe operating temperatures.

In addition to the performance data, Figs. 7 and 8 show cooling air pressure drop and fan power based on fan efficiency of 50 percent. Fan efficiencies of 50 percent and higher are attainable but many installations will show considerably less than this. At rated speed of 3,000 RPM the cooling requirement is not greater than 5 percent of the gross output. The average military installation, however, does not give this low cooling power absorption, since it is necessary to provide extra capacity over and above engine requirements for (a) air inlet and outlet ducting loss, (b) margin for high ambient temperatures, (c) engine oil cooling, and (d) transmission oil coolers where torque converters are used. In general, the vehicle engine can be cooled for about 5 to 10 percent of gross power where the HP/cu.in. is in the region of .47, and may be less than this if vehicle motion supplies some of the cooling work.

Most recent military vehicles, as well as some commercial installations, use torque converters, and this has a decidedly beneficial effect on engine design. The torque converter obviates the necessity for low speed full throttle engine operation, making it possible (a) to use manifolds and valve timing which favor high output at high speeds, and (b) simplify cooling fan selection.

The cooling air flow may be either from fan to cylinders or reverse, commonly referred to as pressure or suction cooling. Excellent results may be obtained by either method, but the suction cooling has the disadvantage of requiring about 1 percent more of the gross engine power due to the increased air temperature to the fan and, in addition the lack of turbulence, ordinarily found at the fan outlet, is sometimes a disadvantage.

For a given cylinder design the operating metal temperatures depend on the cooling air quantities supplied and the effectiveness of the cylinders' utilization of this air. Assuming no leakage of air and proper direction of the air by good baffle arrangements, the air flow required is from 15 to 20 CFM per H.P. for both cylinder sizes operating at the output levels in the range .47 to .56 HP/cu.in. The cooling air requirements can be varied by changes in the fin area, and high output aircraft engines have about twice the fin area of the vehicle engines described here. In this case the extra area is exploited to obtain increased output. If there was need to reduce the cooling air flow on vehicle engines, considerable saving on fan power could be effected by increased fin area, but at increased cost of the cylinders. The finning used in these vehicle engines is not considered expensive or difficult to manufacture.

In comparing the weight of air-cooled engines with liquid-cooled, it is necessary to include the weight of all components of the cooling system. Figure 11 gives weight comparison on this basis and includes all accessories essential to the operation of the engine as well. This shows that the air-cooled engines are about one-third the weight of liquid-cooled, heavy duty vehicle engines where cast iron is the basic material for the liquid-cooled engines. If aluminum were to be substituted for cast iron, the liquid-cooled engine installation would probably still be 70 percent heavier than the air-cooled power plant. In this connection it is of interest to note that the air-cooled vehicle engines are approximately 40 percent aluminum, 50 percent steel or non-ferrous, 10 percent accessories. Liquid-cooled passenger car engine installed weight is somewhat less than the heavy duty engine figure of 10 lbs/HP in that the best examples are about 6 lbs/HP or about twice that of air-cooled engines.

The horizontally-opposed cylinder arrangement conserves weight when compared to the in-line engine for the following major reasons: (a) no counterweights required on the crankshaft; (b) less crankcase metal required for given stiffness of crankcase in fore and aft plane. Further saving is associated with the air-cooled construction of the cylinder since the loads from combustion pressures are transferred to the crankcase by a basically thin wall (.100-inch) steel cylinder as compared to the much heavier wall cast iron cylinder of liquid-cooled engines.

In the design of the engines, full use was made of experimental stress analysis methods as described in several papers by W. T. Bean (Ref. 3). The practical result is parts which are easier to manufacture, as well as lighter for the same endurance life. Figure 12 shows some parts which have been analyzed by experimental stress methods and, in particular, by the use of Stress-coat. Figure 13 shows a crankcase casting having a minimum of ribs and with well-blended sections making for easy casting. Figure 14 is a photograph of a crankshaft study where two crankcheek designs were evaluated. This indicates that it is desirable to make the crankcheek between two crankpins rather wide and relatively thin in comparison with normal practice. Figure 15 shows the stress results on the 149 cu. in. cylinder connecting rod from inertia loading. Long experience in building lightweight aircraft power plants for personal aircraft, helicopters, and light transport types has indicated certain design principles to be lightweight and, at the same time, adequate from the load carrying viewpoint. All such aircraft practices which have been proven adequate and, at the same time not expensive, have been incorporated in the vehicle engines. One example of this is given in the crankcase flange design of Fig. 16.

Provisions for reducing crankshaft stress due to torsional vibration has been made by using pendulum-type dampers on all engines. In some cases the vehicle drive system alters the vibration characteristics so that the dampers will not be required, in which case they can be omitted. Figure 17 shows the dampers as used on the AO-536 and on the AV-1790 engines.

Fuel metering and equality of mixture distribution to all cylinders has been satisfactory in most cases without resorting to manifold hot spot heat, although they are provided to improve warm-up characteristics. One of the most interesting engines in the line in this respect is the AO-536 which can be used with the crankshaft either vertical or horizontal. Figure 18 shows a mixture distribution curve on the vertical model with carburetor at full throttle and no hot spot heat with the cylinder peak temperatures used as an indication of mixture distribution. There is little indication of influence of gravity on mixture distribution, and this is true at part throttle as well. Figure 19 shows the AO-536 engine with fuel injection replacing the carburetor, and the distribution of the engine with this equipment is shown in Fig. 18.

Figure 11 shows that the basic weight of the vehicle engines is about 10 percent greater than the aircraft engines of comparable size, and this extra weight was designed into the engines in order to reduce bearing loads, temperatures and cost, and to insure extra long life. Standard aircraft design practice, though more expensive, might have been used with safety since experience indicated that aircraft service is more demanding on high stressed parts than vehicle service. Vehicle service does require part load operating conditions not found in ordinary aircraft service and one of these is extremely low oil consumption and quiet piston operation as compared to aircraft standards. For this reason, the vehicle engines use longer connection rods and pistons than aircraft engines, as shown by the comparison in the photograph, Fig. 20, which is of parts from an aircraft engine, the air-cooled vehicle engine, and a widely used truck engine, all having the same stroke. Figure 21 gives the oil consumption of several liquid-cooled vehicle engines compared to the oil consumption of the air-cooled engines.

In installing the air-cooled engine, a great variety of choices are available which make for versatility of the power plant. The first consideration in installation is proper path for the cooling air and, at the same time, maximum accessibility. The cooling system should not have constricted air entrance or exit ducts, and velocities of 45 ft/sec. are ordinarily recommended. The air may be discharged from the fan into a plenum chamber ahead of the cylinders, exemplified by the Army Ordnance vehicle T-51 shown in Figs. 22 and 25. An equally effective arrangement incorporates, as part of the engine, all ducting between the fan and power plant, as shown in the 402 engine, Fig. 1. The former method has the advantage of permitting more accessibility to the engine when the installation space is limited. For military vehicles it is necessary to eliminate belt drives for the fan and it is also necessary to provide a method of unloading the fan for underwater operation so as not to overload the fan drive. A centrifugally actuated fan drive friction clutch gives the required action. An alternative method is by eddy-current electric drive, and this device has the additional advantage of providing temperature control for the cylinders. This is done by using a temperature-sensitive element on the cylinders which controls current to the clutch, thus regulating the fan speed to suit the cylinder temperature. These drive devices and fans are shown in Fig. 23.

The 149 cu.in. cylinder used on the 1790 differs from the 67 cu.in. cylinder in that valves are actuated by overhead cam and rocker arms rather than by push rod, as shown in Figs. 3 and 4. The overhead cam is a convenient way of obtaining a hemispherical combustion chamber which is advantageous in the larger cylinders. Other components of the larger engines are conventional, but the engine is designed with low stress as compared to aircraft practice and this is reflected somewhat in the weight.

As shown in Fig. 24, this engine is suction-cooled so that the heated air can be discharged from the vehicle in the shortest possible space, thus reducing engine compartment heating. In addition to this, the cool entrance air is circulated over the gas tanks before entering the engine, thus making for the lowest fuel temperatures and reduced vapor lock tendencies.

The 149 cu.in. cylinder is also made in a horizontally-opposed 6-cylinder supercharged engine of 895 cu.in. displacement, Fig. 2. This engine operates at 158 BMEP at 2800 RPM (as compared to 118 BMEP for the unsupercharged cylinder), which is about the limit of the engine for 80 octane gasoline.

All engines are required to perform a minimum of 500 hours testing under cycling conditions with cooling air temperatures of 120 to 140° F so that a great variety of vehicle loads are duplicated. In general, these tests have shown the

value of such features as nitrided crankshafts, chrome plated piston rings, silver bearings, hydraulic valve clearance adjusters, and pendulum-type crankshaft dampers.

Figure 25 shows the advantage of the vertical installation in one military vehicle. The saving in length over the conventional liquid-cooled heavy duty engine shortens the vehicle length about 26 inches. The shortening of the vehicle also contributes to chassis weight savings and improved driver visibility.

The AO-536 engine is suitable for bus use either with the crankshaft horizontal or vertical as shown in Fig. 26. In this design the engine is extremely accessible because of the components requiring adjustment are all on the rearward side of the engine. This engine saves about 1600 pounds of weight, which is equivalent to 10 passengers. Assuming bus operation at maximum capacity, this weight saving is worth $800 to $1600 per year in accordance with ordinary bus evaluation of weight.

Table II summarizes opinion of how the air-cooled and the liquid-cooled engine compare. This table will be elaborated on by discussion of each item.

1. Freedom from plumbing difficulties is the obvious advantage of air-cooled engines. The average water-cooled engine coolant system has 4 to 40 hose clamps, with passenger car averaging about 6. These are all potential points of leakage and together with the water pump and the jacket plugs and gaskets form literally hundreds of places for leakage trouble. Service records show that about 20 percent of service interruptions are caused by cooling system fault, and nearly all of these are of the type which can be eliminated by the air-cooled engine.

2. Anti-freeze troubles are listed separately since they form such a severe problem in a great many regions of the world. From the military view the anti-freeze problem is particularly troublesome, but commercial operations are equally plagued with the complaint. Some fleet operators use the procedure of letting engines idle for hours or drainage of system rather than contend with the expense and uncertainty of ordinary anti-freeze protection. In addition to the freezing problem, liquid-cooled engines suffer from clogging of the radiator and cooling system by corrosion material resulting from anti-freeze action as well as from salt deposits contained in the water. Clogging of air-cooled cylinder fins with dirt is not often encountered even in the extremes of military use. This is probably because the fins are so closely associated with the shock of combustion which shakes ordinary deposits loose. An exception to this is where air-cooling fins are sometimes blocked in amphibian vehicle service when waves breaking over the engine compartment put solid salt water through the fins with the result that some salt remains on the fins until a build-up results in clogging. A fair percent of fin area can be clogged in this manner without any interference with engine operation. This compares with the liquid-cooled radiator which is quite susceptible to clogging, both on the air and the water side. It seems clear from air-cooled engine experience that no trouble with fin clogging will be experienced in ordinary service in vehicles.

3. The air-cooled engine is basically lighter, especially when built in the horizontally-opposed arrangement. This is because present air-cooled engine practice makes very efficient use of metals by efficient design. Avoidance of structure duplication and stress concentration in the load carrying parts results in basic savings. Studies show that air-cooled engines have less volume of metal in the cylinder from the crankcase out

3. (Continued)

to the tip of the cylinder. In addition, most of this is aluminum so that a double savings is effected. Cylinders on the air-cooled engine are made with about .100-inch wall thickness while the cast iron engine must use about .250-inch wall. The bolted cylinder head construction used on the cast iron engines is wasteful of metal since the bolts are stress concentrators which require additional metal to reduce stress and give stiffness at the required places.

All indications are that the installed engine weight of the air-cooled engine will be about one-half that of the liquid-cooled engine even if aluminum is substituted for cast iron insofar as possible in the liquid-cooled engine. This presupposes that the corrosion and leakage problems of aluminum water jackets can be dealt with in an economical manner, which is doubtful.

4. There is ample experimental evidence to show that air-cooled engines can be made so that less power is wasted in cooling. Where there is no assist from forward motion of the vehicle, the engine power used for cooling can economically be in the region of 5 percent of gross power. At a vehicle speed of about 70 mph, no cooling power would be required of the fan but all cooling effort would come from air ram. Between these two extremes there is opportunity for much compromise as is now practiced in vehicles made for various conditions of operation.

5. Since the quantity of air required for cooling is about one-half for the air-cooled engine, smaller ducts for entrance and exit to and from the engine are required, and this is a distinct advantage in most vehicles since less volume inside the vehicle is wasted in this manner.

6. Air-cooled engines have higher temperatures of the air leaving the engine, and in some cases additional temperature insulation may be required for passenger comfort. This is ordinarily not a serious handicap and in many installations is no handicap whatever since sound and heat insulation is already provided.

7. Some liquid-cooled engines, and in particular L-head engines, lose up to 14 percent in power during the first 100 hours of operation. This power reduction is mostly due to volumetric efficiency loss and is not observed in air-cooled engines since deposits do not build up to as great a thickness, probably due to somewhat higher average (not maximum) combustion wall temperatures in the air-cooled engines.

8. Since 50 percent of the weight of the air-cooled engines is of parts of the same type and workmanship as on liquid-cooled engines, this much of the comparison will show equal cost. The accessories comprise an additional 10 percent of the engine weight and the same type of accessories may be used on either engine. Figure 29 shows those structural parts which are the same in both types of engines and Fig. 30 is a photograph of dissimilar parts. In addition, these photographs show parts of an aircraft engine in order to emphasize the similarity in appearance of the three types. This leaves 40 percent of the weight to be compared for costs. The air-cooled engine uses aluminum for the cylinder head and crankcase as compared to cast iron for the liquid-cooled, and examination of the cost of these materials shows there is no reason to claim extra cost because aluminum is more expensive on a cost per pound basis. Present aluminum

8. (Continued)

castings of the cylinder head type cost about 25 percent more than cast iron liquid-cooled types on a cost per cubic inch basis. Since cast iron and aluminum have about the same strength and are used at about equal stress levels, there will be about equal volumes of metal required which would result in 25 percent more cost for the aluminum parts. This increase in cost is offset by some reduction in metal volume found in present design so that the cost of the two types of cylinder head castings are about equal. Aluminum is generally more economical machining so that a saving is made here as well as in scrap waste since the individual cylinder construction of the air-cooled engine uses smaller parts which results in less expensive parts wasted when scrap occurs. The size and design of air-cooled engine parts permits casting by permanent mold or die casting methods which can give still further economies. Detailed comparison of crankcase cost shows a similar equality of cost for the two types of engines.

It is necessary to consider production rates when considering costs, since it is well recognized that this is the overwhelming factor in reducing costs. Air-cooled engines, and liquid-cooled engines as well, probably do not reach minimum cost until produced at the rate of about 100,000 engines per year. There are no cost comparisons at this production rate but there are some excellent comparisons in the range of 6,000 engines per year. This is a comparison between an air-cooled aircraft engine of about 185 HP and a liquid-cooled engine of the same power. These engines each sell for the same cost per horsepower. This comparison in unfair to the air-cooled type since some expensive traditions are observed on present aircraft engines, such as the use of light weight starters and generators, aircraft type dual magnetos, expensive type carburetors to give altitude compensation and precise metering. In addition, the production testing procedure is more expensize in aircraft engine manufacture.

From these facts and from opinions collected from production experts experienced with both types of engines, it is concluded that air-cooled vehicle engines when produced atlow yearly rates may be equal in cost per horsepower, and at high yearly rates the air-cooled engine may be less than liquid-cooled types.

9. Tradition, experience and prejudice are overwhelming factors in favor of present types of liquid-cooled engines, especially in the automobile industry where tremendous capital has been invested in machinery and equipment for cast iron engine production. It is recognized that there is sound reason for not risking a change from the conventional. However, very careful evaluation of the hazards and the gains to be realized may give different conclusions when weighed by different organizations having differing plant and marketing conditions.

Considering the switch from liquid-cooled engines to air-cooled engines from the manufacturing viewpoint only, the percentage of parts that differ is rather small as examination of the 67 cu.in. cylinder engine line will reveal and as might be surmised from the discussion of costs in Item 8. The evaluation of Table II rates the existing manufacturing establishment as equally suitable for both types since there is really one dissimilar part on the two types -- the cylinder heads, with all other parts capable of being made with the liquid-cooled engine machinery and equipment. The automotive industry is quite accustomed to aluminum crankcase designs and present machinery would lend itself to this design. In any case, cast iron might be used for the

9. (Continued)

crankcase and the weight penalty suffered. There remains then, only the cylinder and the cylinder head to evaluate from the plant and machinery standpoint, and these must be aluminum for heat conductivity reasons. These parts are small enough to be made advantageously by die castings and automatic machinery methods, and the multiple cylinder use justified the most advanced type of cost saving machinery and tooling.

10. Serviceability, that is, ease and cost of replacing worn parts is about equal in most evaluations. The advantage of individual cylinder construction is partly offset in the designs herein described by the crankshaft inaccessibility. If crankshaft accessibility is considered important, conventional crankcase and bearing cap construction may be used in the opposed cylinder construction. It should be realized that the particular designs shown in these engines are by no means requisite, and evaluation of air-cooling should not be confused by the special features of this design. An adequate background of modern, proven air-cooled engine alternative design exists from which to choose the most suitable for particular conditions of use or of manufacturing facilities.

11. The air-cooled engine has a background of service life information established in the aircraft industry and in military use in this country and in Europe during the last 20 years, including about 30,000,000 horsepower installed in tanks used in the last war. This record indicates that the air-cooled engine is the equal of present day liquid-cooled vehicle engines. As an aside, it may be of interest to state our opinion on the relative severity of the engine service on aircraft as opposed to military vehicles. Service records seem to indicate that the aircraft experience is more severe in those regions where fatigue stress is critical, such as in bearings, crankshafts, highly stressed screw fasteners and studs, etc., while the military usage is more severe in those places where abuse predominates, such as faults from over-speeding, sand in engine from inadequate or unserviced air cleaners, etc.

12. Noise is generally regarded as more severe in air-cooled engines than in liquid-cooled engines since it is maintained that the water and extra metal density of the liquid-cooled give sound suppression. It is difficult to refute the argument since there have been no quiet air-cooled engines developed because the demand for quieter operation has not been great until recently. It is interesting to note that aircraft engines may shortly be in a position to demonstrate quiet operation since in the small private airplane class the major noise producers have been reduced to the point where accessory drive spur gear noise is audible and spiral gears are indicated. In any case, the modern vehicle requires sound insulation between present liquid-cooled engines and the passengers, and it is felt that this will also be adequate for the air-cooled engine.

13. Air-cooled engines operate under more favorable conditions in the cold or in warm-up process since there is less thermal lag because of less mass. In addition, there is beneficial effect from the warmer intake port in the cylinder head, the net result being less warm-up difficulties and better cold operation. These effects are difficult of evaluation but the statement is based on views expressed by many operator observers. Sludge difficulties in the oil system appear to be much less in air-cooled engines, probably due to faster warm-up and to higher temperatures in the lower region of the piston travel and in the valve spring chamber.

14. Oil consumption appears equal, as discussed in connection with Fig. 21.

15. Detonation is about equal at equal power output conditions, although the air-cooled engine will probably have lower compression ratio than the liquid-cooled engine. This does not imply more fuel consumption, but quite the contrary.

16. There is little to choose between the two engine types on fuel consumption when developed to use the same octane fuel, although equality of output and fuel consumption is obtained at lower compression ratios in the case of the air-cooled engine, however, this is of little practical significance.

In speculating on the most profitable method of exploiting the air-cooled engine for passenger car use, the rear engine car comes in for consideration. Normally, placing the engine in the rear overloads the rear wheels and creates an unbalance in weight distribution between the front and rear wheels. Reducing the power plant weight introduces some possibilities of correction of the weight distribution faults, and still further benefits can be realized by vertical crankshaft mounting as shown in the 6-cylinder, 75-HP engine in Fig. 27. Figure 28 is of a front engine conventional installation where the air-cooled engine weight saving and short length would probably be useful in improving steering by taking load off the front wheels and in improving passenger disposal. In this case, an 8-cylinder engine of 100 HP is shown. The two engines shown have not yet been built but the design and performance have been carefully estimated from the vehicle engines described earlier. These engines are rated at 3800 RPM to conform with automotive practice and the installed weights are slightly less than 3 pounds/horsepower depending on accessories chosen.

Assuming that the air-cooled installation can be had for 3 pounds/horsepower and the liquid-cooled for 6 pounds/horsepower and on the basis of a 100-HP liquid-cooled engine, the weight saving of the air-cooled engine would be 300 pounds. It seems reasonable to expect that other weight savings could be effected because of the initial weight saving in the engine. This added to some weight saving from rear engine arrangement should result in a total weight saving, according to some passenger car authorities, of about 600 pounds total. With a weight of vehicle to power ratio of 30:1, a 600-pound weight savings would permit 20 HP reduction of engine size for the same vehicle weight to power ratio.

To summarize, it appears that from the engineering, performance, and economic viewpoints the air-cooled engine can replace the cast iron liquid-cooled engine with some very important advantages to be realized from the air-cooled types. It remains to be proven by commercial experience that the air-cooled engine can meet the commercial requirements, although military use would forecast equality in this respect. It also remains to be determined whether or not human inertia or prejudice will be major deterrents in the acceptance of air-cooled engines in commercial vehicles.

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NOTE: Due to the fact that line drawings and halftones have been grouped on separate sheets, illustrations are not reproduced in correct sequence.

AIR COOLED VEHICLE ENGINE DATA

MODEL	NO. OF CYLS	DISP	BORE AND STROKE	SUPER-CHARGED	COMP. RATIO	RATED BHP AT RPM	RATED BMEP	WEIGHT LB.	HP PER CU.IN.	LENGTH INS.	HEIGHT INS.	WIDTH INS.	C'SHAFT VERTICAL OR HORIZ
AO-268-2	4	268	4.62 X 4.00	NO	6.7	125-3000	123	560	.466	28.88	32.25	36.25	V OR H
AO-402-2	6	402	4.62 X 4.00	NO	6.7	190-3000	124	675	.472	35.94	32.10	36.12	V OR H
AO-536-1	8	536	4.62 X 4.00	NO	6.7	250-3000	123	777	.466	38.31	27.37	35.12	V OR H
AO-895-2	6	895	5.75 X 5.75	NO	6.5	375-2800	118	1650	.419	46.78	39.96	50.72	HORIZ.
AOS-895-1	6	895	5.75 X 5.75	YES	5.5	500-2800	158	1680	.560	45.33	34.59	50.72	HORIZ.
AV-1195-1	8	1195	5.75 X 5.75	NO	6.5	540-2800	128	1865	.452	50.38	38.69	61.12	HORIZ.
AVS-1195	8	1195	5.75 X 5.75	YES	5.5	665-2800	158	1985	.556	50.38	38.69	54.35	HORIZ.
AV-1790-3	12	1790	5.75 X 5.75	NO	6.5	810-2800	128	2380	.452	66.88	38.69	61.12	HORIZ.
AVS-1790-4	12	1790	5.75 X 5.75	YES	5.5	1000-2800	158	2500	.560	66.88	38.69	54.35	HORIZ.

TABLE I

TABLE II

COMPARISON OF AIR AND LIQUID-COOLED ENGINES

		Advantage For	
		Air	Liquid
1.	Plumbing difficulties	X	
2.	Anti-freeze requirements	X	
3.	Weight	X	
4.	Fan power	X	
5.	Quantity of cooling air required	X	
6.	Temperature of cooling air leaving engine		X
7.	Power loss due to combustion chamber deposits	X	
8.	Costs	X	X
9.	Established manufacturing equipment for high production	X	X
10.	Serviceability	X	
11.	Long life	X	X
12.	Noise	X	X
13.	Cold operation	X	
14.	Oil consumption	X	X
15.	Anti-detonation quality	X	X
16.	Fuel consumption	X	X

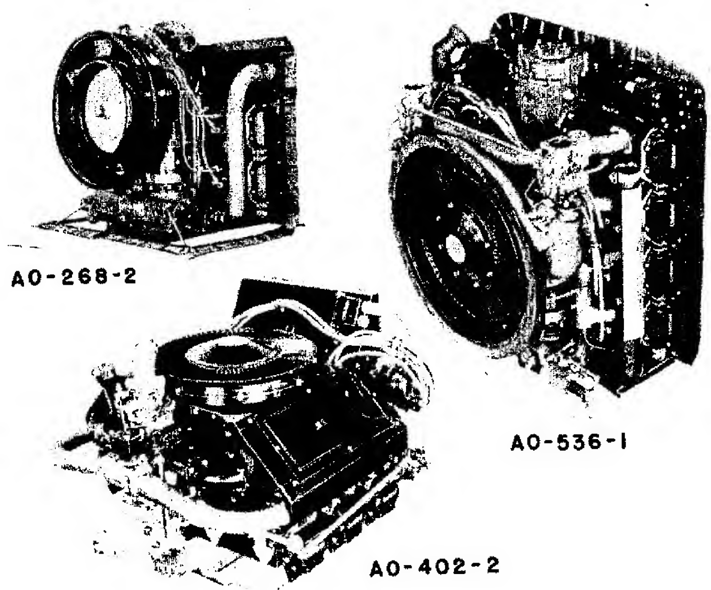


FIG. 1 67 CU. IN. LINE OF ENGINES

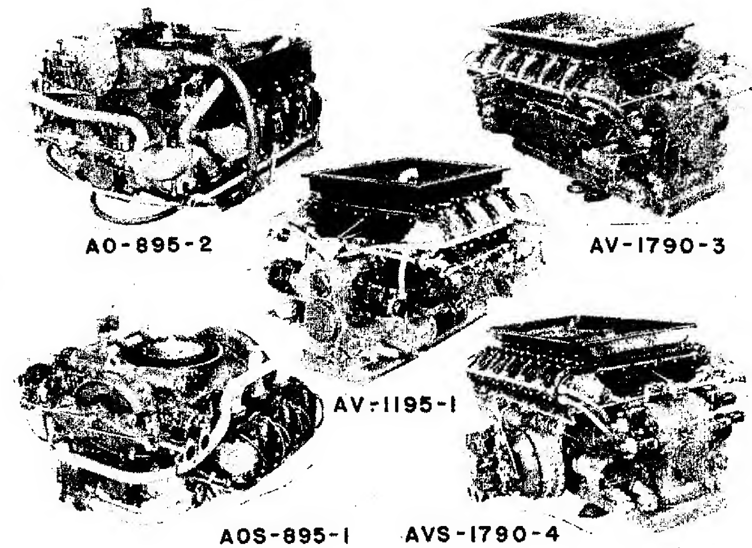


FIG. 2 149 CU. IN. LINE OF ENGINES

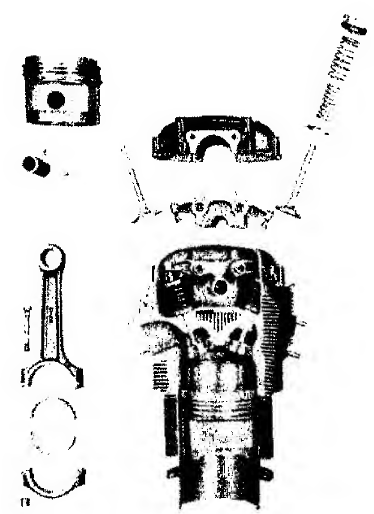


FIG. 3 149 CU. IN. CYLINDER AND INTERCHANGABLE PARTS.

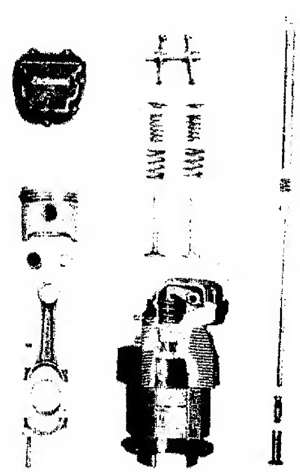


FIG. 4 67 CU. IN. CYLINDER AND INTERCHANGABLE PARTS.

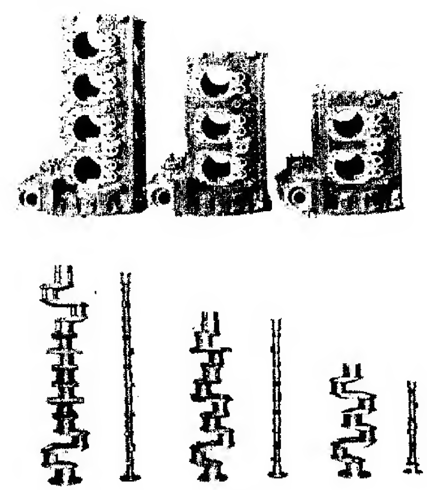


FIG. 5

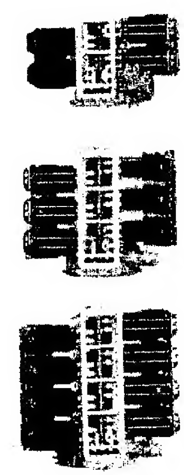


FIG. 6

COMPONENTS OF THE 67 CU. IN. CYLINDER LINE SHOWING SIMILARITY OF PARTS FOR THE 4 - 6 - AND 8 CYLINDER ENGINES.

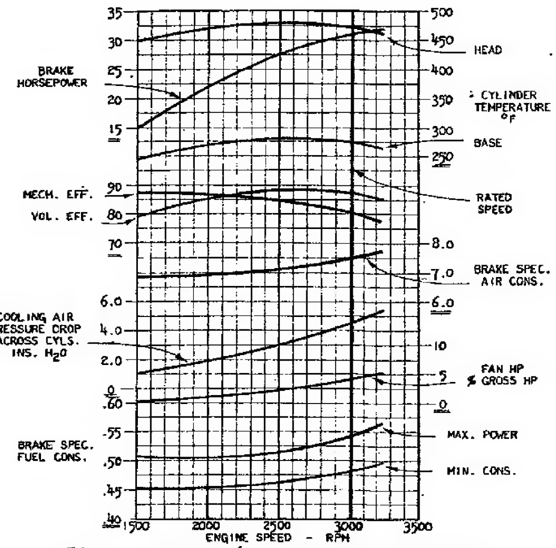


FIG. 7 PERFORMANCE OF 67 CU. IN. CYLINDER AT FULL THROTTLE

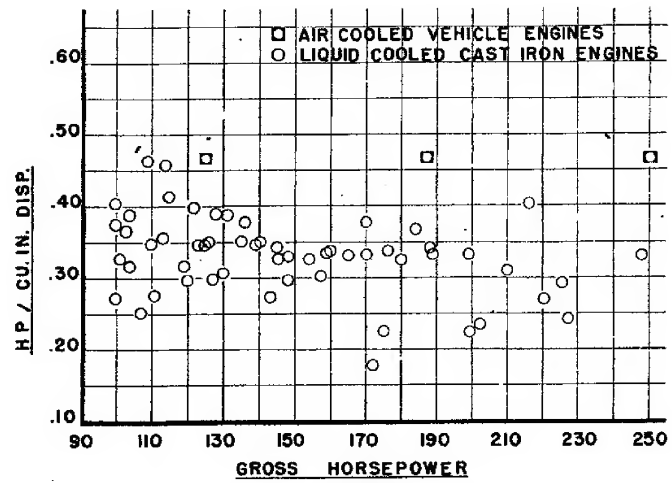


FIG. 9

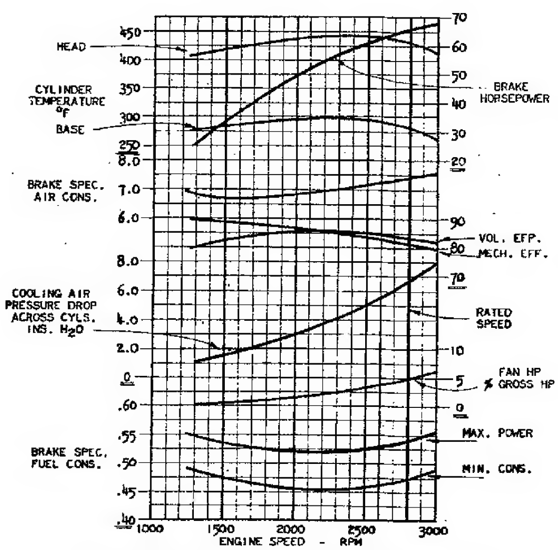
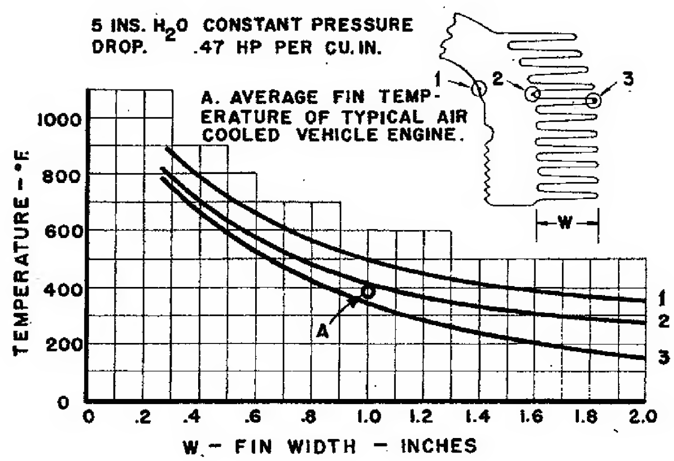


FIG. 8 PERFORMANCE OF 149 CU. IN. CYLINDER AT FULL THROTTLE



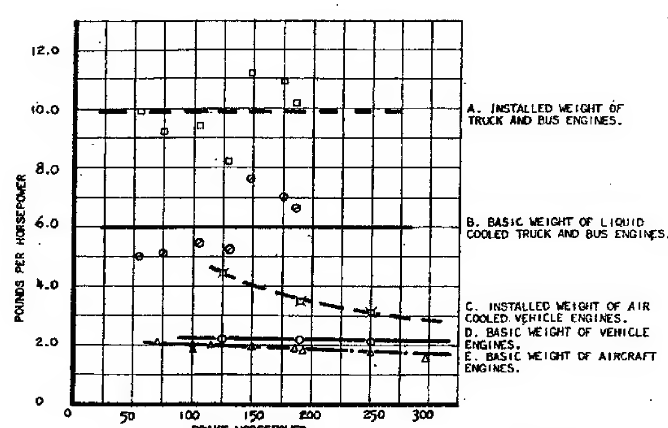


FIG. 11 COMPARISON OF WEIGHTS OF AIR COOLED VS. LIQUID COOLED ENGINES.

(BACHLE)

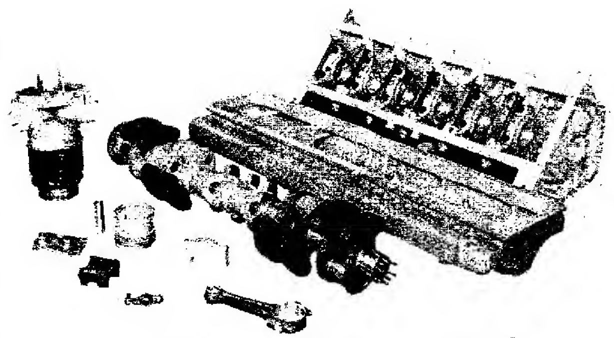


FIG. 12 SOME PARTS OF THE AV-1790 ENGINE ON WHICH CRITICAL STRESS HAS BEEN DETERMINED BY EXPERIMENTAL METHODS. CYLINDER HEAD HAS FINS REMOVED TO PERMIT STRESSCOAT TESTS.

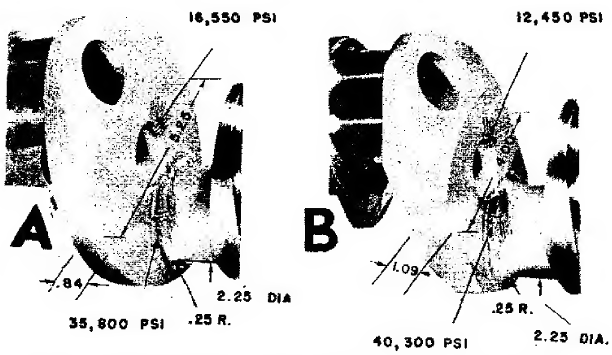


FIG. 14 STRESSCOAT EVALUATION OF TWO CRANKSHAFT DESIGNS. 600 PSI CYL. PRESSURE AT 22 A.T.C. - 4" STROKE. DESIGN 'A' SHOWS 12% LESS STRESS AT THE CRITICAL POINT IN THE CRANKPIN FILLET. THE PROPORTIONS OF 'A' WERE ADOPTED FOR ALL ENGINES

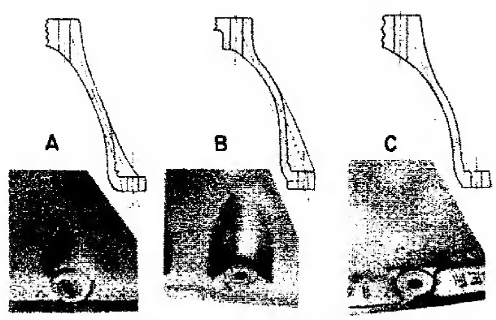


FIG. 16 METHOD OF FLANGE DESIGN FOR ALUMINUM CASTING JOINTS. DESIGN 'A' HAS ABOUT 50% MORE LOAD CARRYING ABILITY THAN DESIGNS 'B' AND 'C'. IN ADDITION DESIGN 'A' IS EASIER TO CAST AND MACHINE.

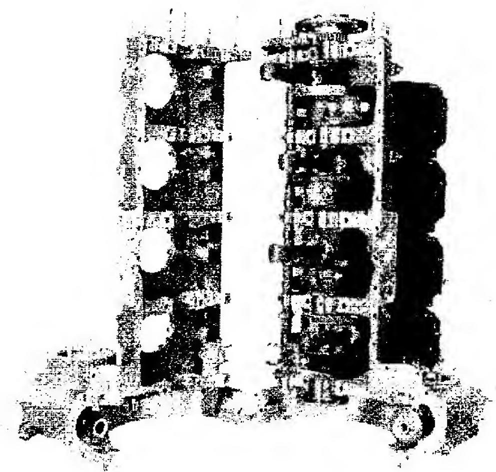


FIG. 13 VIEW OF AO-536 ENGINE INTERIOR WITH CRANKCASE PARTED. NOTE UNRIBBED CRANKCASE DESIGN AND INTEGERAL ACCESSORY DRIVE SECTION.

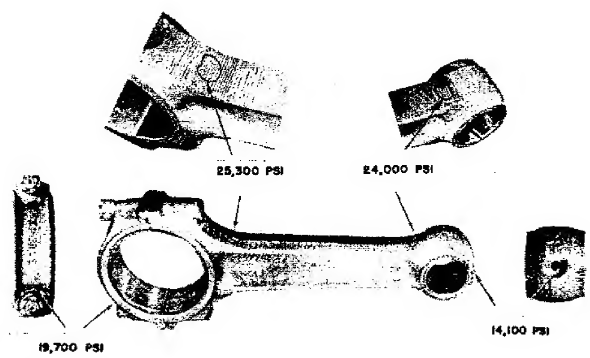


FIG. 15 149 CU.IN. CYLINDER CONNECTING ROD STRESS AT VARIOUS CRITICAL AREAS FOR 110% RATED SPEED.

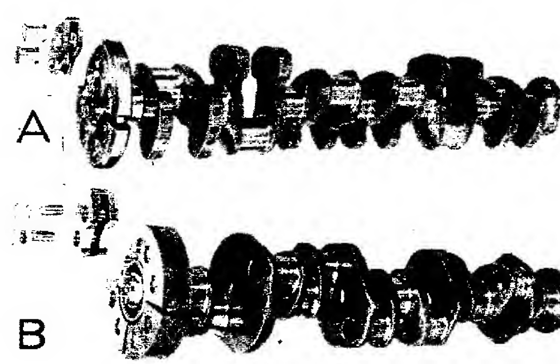
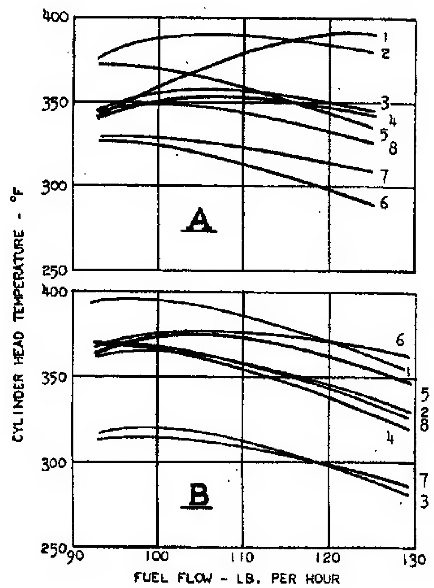


FIG. 17 PENDULUM TYPE TORSOINAL VIBRATION DAMPERS FROM 'A' AV-1790 AND 'B' AO-536 ENGINES.



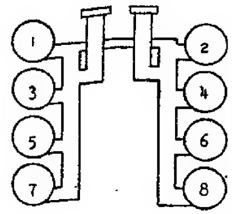


FIG. 18 MIXTURE DISTRIBUTION IN THE AO-536 ENGINE WITH 'A' CARBURETION AND 'B' FUEL INJECTION.

(BACHLE)

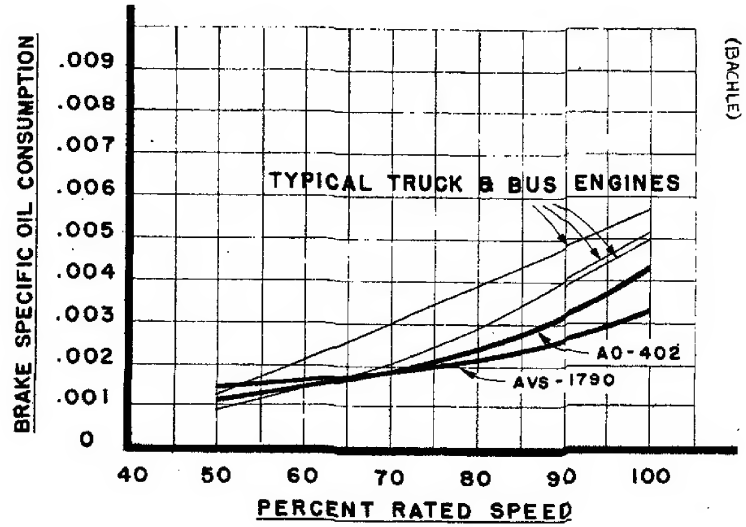


FIG. 21

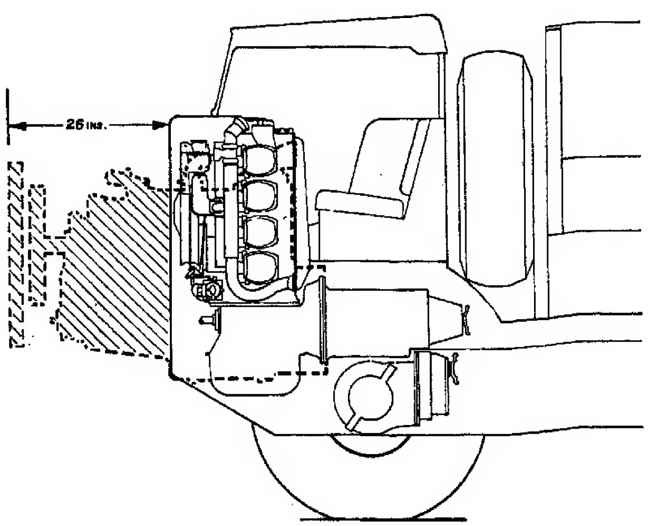


FIG.25 COMPOSITE VIEW OF INSTALLATION OF AIR COOLED VS. LIQUID COOLED ENGINE IN MILITARY VEHICLE.

WEIGHT OF LIQUID COOLED ENGINE WITH COOLING - 2400 LB.
WEIGHT OF AIR COOLED ENGINE WITH COOLING - - - 777 LB.

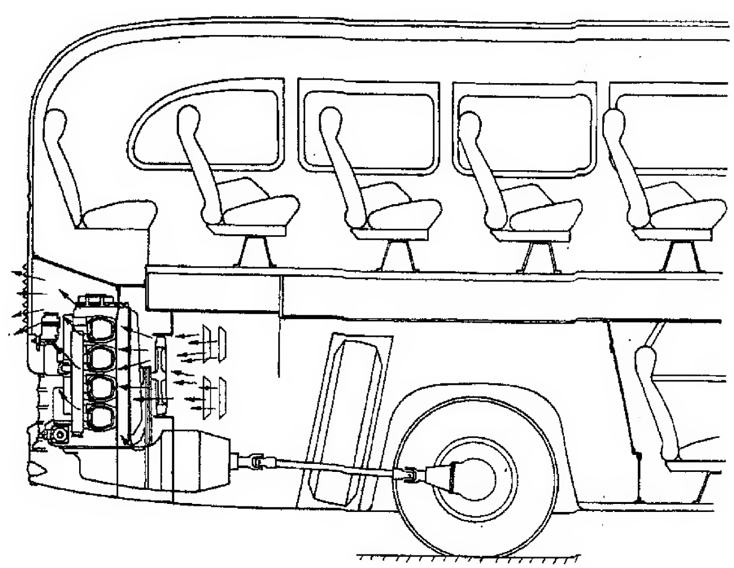


FIG. 26 INSTALLATION OF AO-536 ENGINE IN NEW TYPE BUS

(BACHLE)

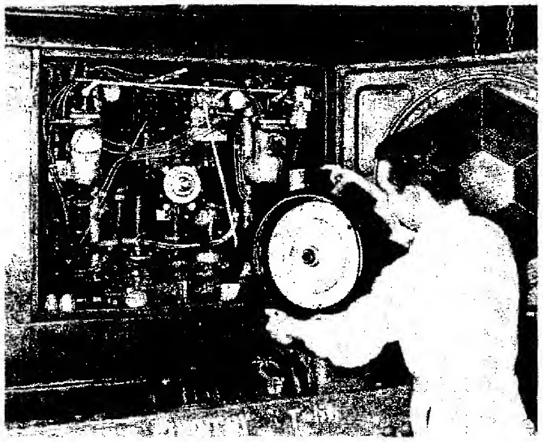


FIG. 19 VERTICAL INSTALLATION OF AO-536-2 ENGINE IN U.S. ARMY ORDNANCE VEHICLE T-51. THIS ENGINE HAS FUEL INJECTION INSTALLED REPLACING CARBURETORS WITH WHICH IT IS NORMALLY EQUIPPED.

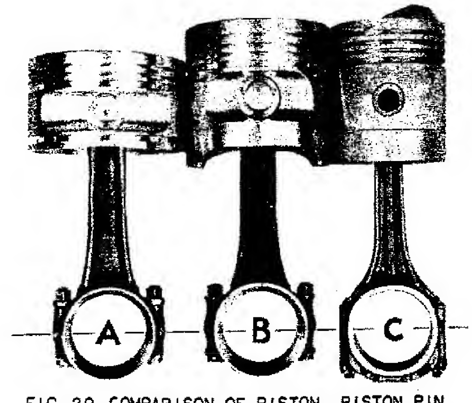


FIG. 20 COMPARISON OF PISTON, PISTON PIN AND CONNECTING ROD FROM 'A' AN AIRCRAFT ENGINE, 'B' AIR COOLED VEHICLE ENGINE AND 'C' A HIGH PRODUCTION TRUCK ENGINE.

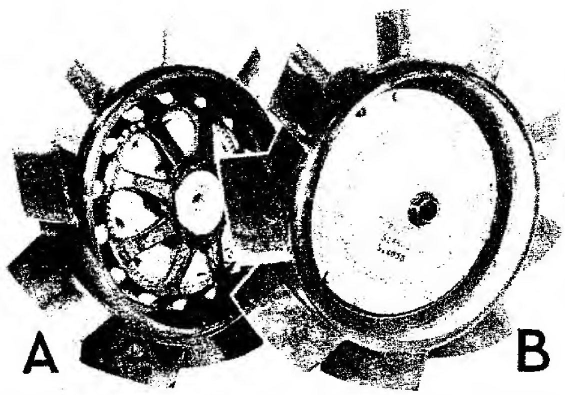


FIG. 23 TWO FAN CLUTCH TYPES. 'A' EDDY CURRENT TYPE AND 'B' CENTRIFUGAL ACTUATED FRICTION TYPE. FAN SHOWN HAS EFFICIENCY OF 47% AT 4000 RPM FOR 6200 CFM AND 11.5 INS. WATER PRESSURE RISE.

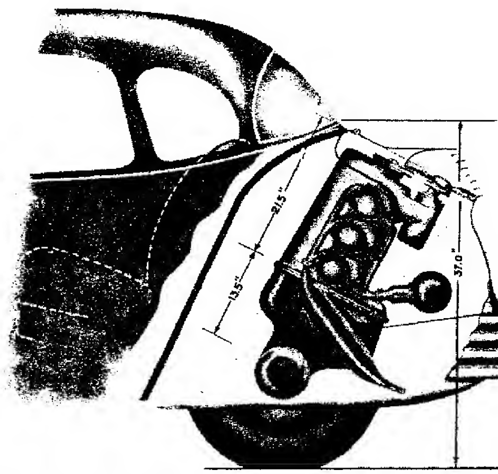


FIG. 27 REAR ENGINE PASSENGER CAR OPPOSED 6-CYLINDER 75 HP - 3800 RPM 225 LBS. INSTALLED WEIGHT.

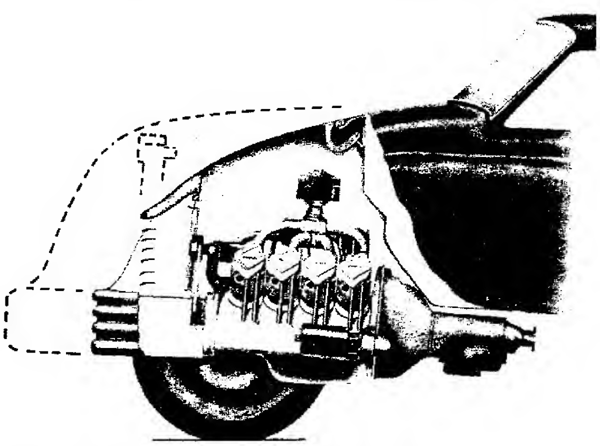


FIG. 28 FRONT ENGINE PASSENGER CAR V8 CYLINDER ENGINE 100 HP - 3800 RPM 300 LBS. INSTALLED WEIGHT

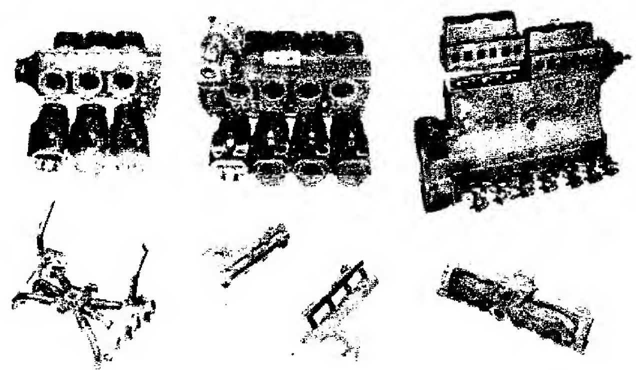


FIG. 30 DISSIMILAR PARTS

(BACHLE)

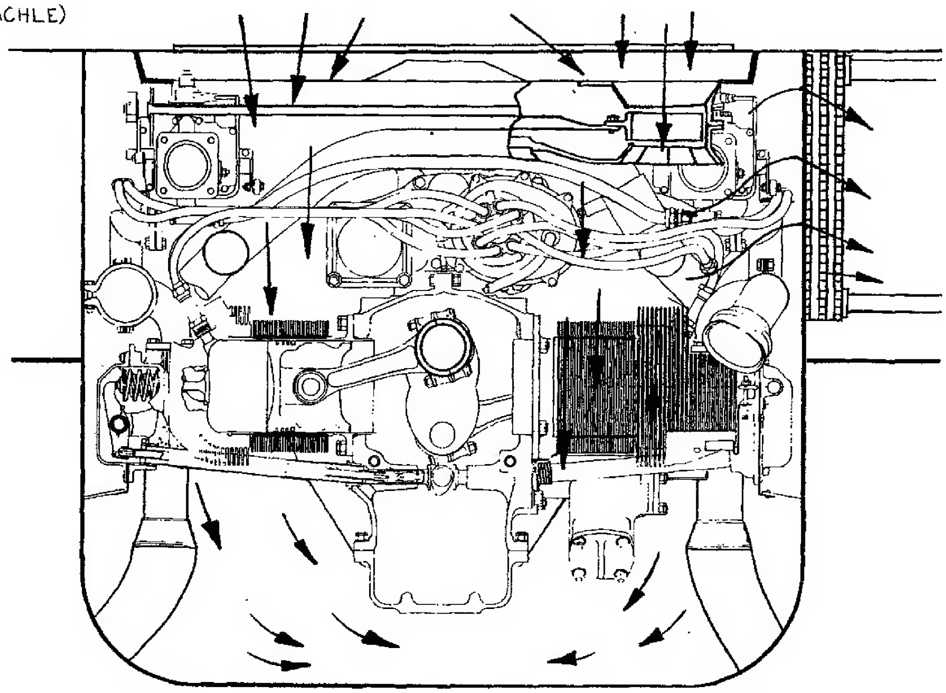


FIG.22 TOP VIEW OF ENGINE COMPARTMENT OF MILITARY VEHICLE SHOWING INSTALLATION OF AO-536 ENGINE.

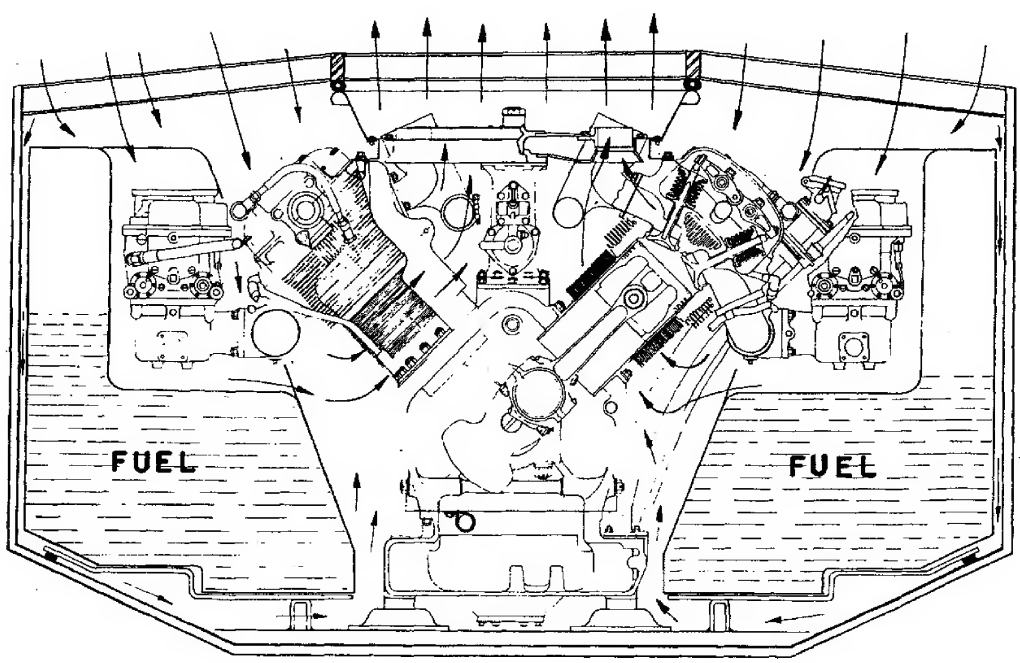
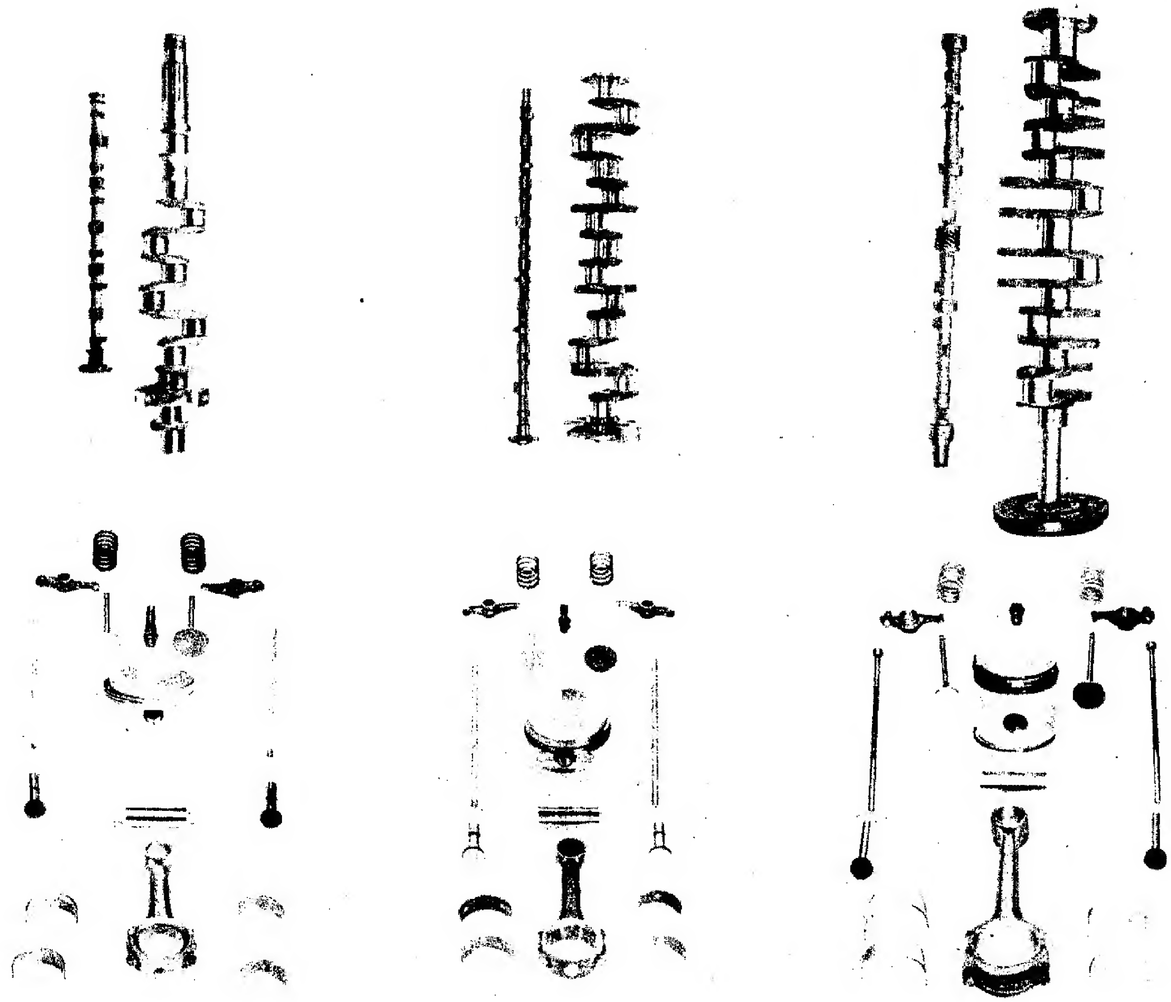


FIG. 24 AV-1790 ENGINE INSTALLED IN MILITARY VEHICLE

(BACHLE)



AIR-COOLED AIRCRAFT AIR-COOLED VEHICLE LIQUID-COOLED

FIG. 29 SIMILAR PARTS